

Variation in Low-temperature Exotherms of Pecan Cultivar Dormant Twigs

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Abstract. Pecan [*Carya illinoensis* (Wangenh.) K. Koch] trees native to northern regions are more cold-tolerant than those native to and grown in the southern United States. To identify a possible assay for cold hardiness, dormant winter twigs from 112 diverse pecan cultivars grown in Texas were surveyed using differential thermal analyses (DTA). The low temperature exotherm (LTE) from DTA was identifiable when twigs were stored at -3°C for up to 120 d after harvest. Thirty-nine percent of the southern pecan cultivars lacked an obvious LTE, and the remaining southern cultivars had an average LTE of -32.9°C . In contrast, only 11% of the northern pecan cultivars lacked the LTE and the remaining cultivars had a significantly lower LTE of -35.4°C . Because twig samples were collected from trees grown in the same Texas orchard, it is suggested that there is a genetic component that affects the temperature of the LTE. Budbreak generally occurred earlier in southern cultivars than those that originated in the north. Both budbreak and LTE data can be correlated with regional origin; timing of budbreak may be preferred over DTA to predict relative cold hardiness in pecan.

Pecan [*Carya illinoensis* (Wangenh.) K. Koch] trees are native to the United States and Mexico with a range that extends from floodplains in Illinois and Iowa through Texas to Mexico (Fig. 1). Trees originating from northern populations mature seeds within a growing season of ≈ 170 d and survive in areas that receive average annual minimum winter temperatures of -26 to -29°C . Trees at the southern extent of the range in Oaxaca, Mexico, may experience no freezing temperature in some years and new growth occurs before dehiscence of the previous season's foliage (Grauke and Thompson, 2008). Observations of seedlings from across the range, grown in a common orchard, allow native populations to be divided into two main provenances. Seedlings originating from southern sources (from Texas south) break bud earlier in the spring, retain foliage later in the fall, and grow larger in height and trunk diameter than seedlings originating from more northern sources (Wood et al., 1998).

To survive in the north, pecan trees must be adapted to withstand the onset of cold temperatures in the fall, to survive extremely cold temperatures in midwinter, and to begin growth only after the danger of a spring freeze is over. In the fall, families of seedlings in provenance orchards can be distinguished by the inception of dormancy with seedlings from southern sources retaining leaves longer in the fall than seedlings grown from northern sources. However, leaf drop is typically initiated for all seedlings after the first frost (0°C), which is received at the Brownwood, TX, worksite by 16 Nov. (5 of 10 years) and at the College Station, TX, worksite by 30 Nov.

The progression of pecan cultivars through winter dormancy has not been well characterized. When pecan seedlings grown from open-pollinated 'Dodd' seeds were given 900 h of chilling at 6°C and were transferred to a greenhouse at 23°C , greater than 50% began growth within 80 d (Smith et al., 1992). Longer periods of chilling reduced time to and increased uniformity of budbreak. Seedlings chilled at 5°C had higher levels of budbreak in both first and second lateral buds after 1000 h than seedlings chilled at either 1 or 9°C . All terminal buds broke at 1000, 1500, 2000, and 2500 h regardless of chilling temperature. However, first lateral buds receiving 1°C chilling had the highest recorded levels of budbreak after 1500 and 2000 h, whereas second lateral buds receiving 5°C continued to show the highest levels of budbreak at those time periods. The

severity of the winter may influence duration of dormancy to different degrees in different areas of a tree, influencing uniformity of budbreak within the canopy. Heating requirements for pecan budbreak have been identified for pecan cultivars that experience minimal chilling (Sparks, 1993). Northern cultivars have greater chilling requirements for budbreak than southern cultivars (Sparks, 1993, 2005; Wood et al., 1998).

Generally, seed development occurs faster and results in early seed maturation in ecotypes from northern latitudes (Daws and Pritchard, 2008; Sparks, 1991). Northern pecan parents have conferred that trait on their progeny in several cultivars such as 'Pawnee' (Thompson and Hunter, 1985), 'Osage' (Thompson et al., 1991), 'Kanza' (Thompson et al., 1997), and 'Lakota' (Thompson et al., 2008). Evaluating seasonal phenology of controlled cross-progeny families is easily done and is useful in predicting the extent to which a genotype fits a targeted environment, but more accurate methods of characterizing hardiness may improve the recognition of critical limitations and influence decisions of cultivar release and deployment.

Differential thermal analyses (DTA) have been used to imply cold hardiness in woody tissues of some species. In apple, pear, and azalea, a low temperature exotherm (LTE) of dormant woody stem sections, detected by DTA, correlated with injury to both xylem and pith that occurred during cooling (Graham and Mullin, 1976; Montano et al., 1987; Quamme et al., 1972a, 1972b). The LTE is an indication of the temperature at which supercooled water, presumably in the xylem, freezes. DTA profiles also show broad exothermic events at higher temperatures, which are usually interpreted as water freezing in extracellular spaces of the xylem and pith. The magnitude of the LTE decreases with slow cooling rates (less than $5^{\circ}\text{C}/\text{h}$) or increased exposure times at subzero temperatures (Quamme et al., 1972a, 1972b, 1973). The correlation between LTE temperatures and mortality led some to suggest that the DTA technique could be used to indicate cold hardiness and Quamme (1991) proposed using LTE temperature as a measurement of cold hardiness in breeding programs for some species. LTE temperatures have previously been shown to correlate with lethal cooling in winter and early spring-harvested pecan apical floral buds and stem samples (Rajashekar and Reid, 1989).

Many factors contribute to cold hardiness in pecan trees: rootstock, crop load, tree age, nutritional status, seasonal growth and weather conditions, cultivar, and ecotype (Grauke and Pratt, 1992; Sanderlin, 2000; Smith, 2000, 2002; Smith et al., 2001; Sparks and Payne, 1977). Our interest here was to survey a broad range of pecan diversity (112 cultivars) to determine if differences in ecotype could be detected by LTE profile.

Materials and Methods

Plant material. Pecan dormant budwood was collected in 1998 and 1999 from the

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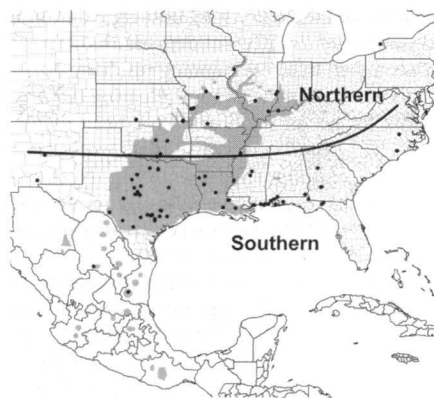


Fig. 1. Geographic origins of pecan cultivars included in 1999 differential thermal analyses. Shaded area indicates the native region of pecan. Latitude 34° N separates the southern region from the northern region for ecotype comparisons.

USDA-ARS National Collection of Genetic Resources in Brownwood and College Station, TX. Cultivars were grouped in relation to the latitude and longitude of their origin (Fig. 1). The two regions were generally consistent with boundaries of ecogeographic regions (Vogel et al., 2005). North latitude 34° was selected as the division between the regions because it is the limit of *Carya* during the Pleistocene glaciation ≈16,000 years ago. It is also close to the latitude (36°) defined for pecan trees that are adapted to a growing season of 210 or more days (Sparks, 1991).

The stage of budbreak was determined in early Apr. 2004 and 2005 at the College Station worksite. Budbreak was scored on a 1 to 9 scale from dormant to fully expanded (Grauke, 2008). Patterns of cultivar performance were similar for the 2 years and previous results suggest that the patterns of budbreak are consistent across many years (Grauke and Thompson, 1996).

Dormant budwood (moisture content between 40% and 47% fresh weight basis) was packaged in plastic bags with damp paper and sent overnight to the USDA-ARS National Center for Genetic Resources Preservation in Ft. Collins, CO, for DTA. Budwood was held in sealed plastic bags at ≈−3 °C until analyses were performed. Three cultivars, Frutoso (state of Coahuila, Mexico), Burkett (Callahan County, TX), and Hodge (Clark County, IL), were collected in Dec. 1998, Jan. 1998, and Mar. 1999 from the Brownwood, TX, worksite and budwood was held in plastic bags at −3 °C for 0, 1 to 2

months, and 3 to 4 months after collection before LTE determination. Budwood for 112 diverse pecan cultivars was collected on 6 Jan. 1999 from the College Station worksite and changes of LTE profiles were compared for storage durations of 0 to 35, 37 to 70, 90 to 120, and 150 to 181 d.

For DTA, dormant budwood was prepared by drilling holes 1 cm deep into stem sections that were 2.5 to 3 cm in length and cut from the current season's growth at least 4 cm below the tip of the terminal bud. Sections were placed on four of five thermocouples (type T, 30 gauge) wired together in parallel in an aluminum block. The fifth thermocouple served as a reference and was covered with a mass of aluminum foil. The aluminum block assembly was placed in a Cryomed freezer (Cryomed, Mt. Clemens, MI) and cooled at −0.2 °C/min to at least ≈50 °C (12 °C/h). Thermocouple voltages were monitored and recorded with a 12-bit data acquisition system (Intelligent Instrumentation, Tucson, AZ). LTE was detected as the temperature where the lowest peak began. DTA traces that did not produce significant LTE (the average slope of the DTA was less than 3×10^{-6} volts/°C) were considered "flat" traces. All DTA were performed at least twice for each cultivar. Analyses of variance were conducted to determine the main effects of LTE temperature, region of origin, and whether materials originated from wild or cultivated sources.

Results and Discussion

Sometimes cooling rates affect the shape of the LTE. However, in preliminary studies, the temperature of the onset of the LTE did not change when budwood was cooled at rates of 0.6, 3.0, 12, or 24 °C/h (data not shown; similar results reported by Rajashekar and Reid, 1989). In all subsequent analyses, a cooling rate of 12 °C/h resulted in a first exotherm between −5 and −10 °C representing extracellular water that froze as a result of spontaneous nucleation. These ranges are similar to that reported in the literature (Ketchie and Kammereck, 1987).

Low temperature exotherms and harvest date. The LTE was identified in DTA for cultivars Frutoso (Mexico), Burkett (Texas), and Hodge (Illinois) (Fig. 2). Budwood from the cultivars was harvested in December, January, and March and DTA were performed immediately, after 1 to 2 months, and after 3 to 4 months (Table 1). Initially, the LTE of 'Frutoso' was −19 °C in December compared with significantly lower LTE

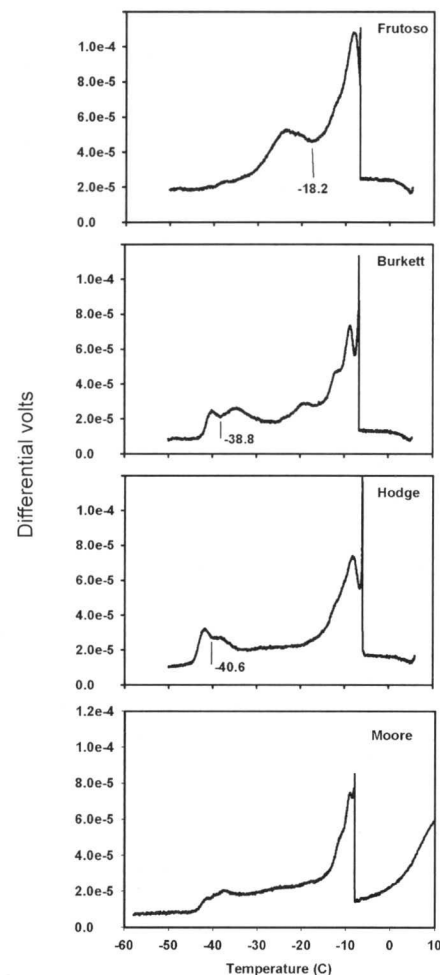


Fig. 2. Representative differential thermal analyses of fresh pecan twigs of 'Frutoso', 'Burkett', and 'Hodge' harvested in Dec. 1998 compared with a "flat" trace of 'Moore' harvested in Jan. 1999. Low temperature exotherms are identified on the traces.

of −39 and −40 °C for 'Burkett' and 'Hodge', respectively. Both 'Hodge' and 'Burkett' retained low LTEs for at least 2 months after the December sampling time point. The LTE of 'Frutoso' was significantly lower when this cultivar was sampled in January and held for up to 4 months (−28 to −31 °C). The LTE of 'Burkett' was similar when it was sampled in January and held for up to 4 months (−25 to −28 °C), whereas the DTA of 'Hodge' was lower (−32 to −36 °C). At the March sampling time point, the LTE for all three cultivars were significantly higher (−16 to −23 °C) than their lowest LTE.

Table 1. Comparison of the onset of the low temperature exotherms (LTE) for three pecan cultivars harvested in Dec., Jan., or Mar. 1999 and held for up to 4 months at −3 °C before differential thermal analyses.^a

Collection mo.	Frutoso, Mexico			Burkett, TX			Hodge, IL		
	0 mo	1–2 mo	3–4 mo	0 mo	1–2 mo	3–4 mo	0 mo	1–2 mo	3–4 mo
Dec.	−19 ± 0.3	n/a	Flat	−39 ± 0.1	−39 ± 0.3	Flat	−40 ± 0.6	−39 ± 0.1	−33 ± 0
Jan.	n/a ^b	−28 ± 2.2	−31 ± 0.6	n/a	−28 ± 0.1	−25 ± 4	n/a	−32 ± 5	−36 ± 0.4
Mar.	−18 ± 0.3	−18 ± 0.3	Flat	−16 ± 0.7	−17 ± 0.4	Flat	−23 ± 5.2	−18 ± 0	Flat

^aMean LTE and SE are provided.

^bNot analyzed.

Table 2. Locality, temperature of the onset of the low temperature exotherm (LTE) (\pm SE), and budbreak data for 112 pecan cultivars.

Plant ID	Inventory designation	Latitude °N	Longitude °W	Region	Source	LTE (°C)	Budbreak	
						1999	2004	2005
Alley	CSV5-3	30.433	-88.533	South	Seedling	Flat	4.5	4
Apache	CSHQ 4.3-1	31.726	-98.973	South	Cross	-31.2 \pm 0.5	6.5	5
Baker	CSV5-4	32.615	-93.287	South	Seedling	Flat	6	4.5
Barton	CSV5-6	31.726	-98.973	South	Cross	-35.3 \pm 0.8	4.5	3
Big Boy	CSV11-4	29.368	-98.424	South	Seedling	Flat	7	6
BoltenS24	CSV10-1	39.385	-87.496	North	Seedling	-35.7 \pm 0.5	6	4
Brake	CSV5-9	35.973	-77.823	South	Native	Flat	7	4
Branch	CSV17-3	30.400	-88.583	South	Seedling	Flat	5	4
Bridges	CSV11-6	33.291	-97.694	South	Seedling	-33.6 \pm 0.2	2	2
Buchel#1	CSV11-7	29.098	-97.285	South	Native	Flat	6	4
Burkett	CSV11-3	32.374	-99.162	South	Native	-28.4 \pm 0.6	5.5	4.7
Caddo	CSHQ7.3-1	31.781	-84.018	South	Cross	-33.5 \pm 0.1	6	5
Cape Fear	CSV18-11	34.690	-77.980	South	Seedling	Flat	6	4
Carden	CSV21-27	31.715	-96.163	South	Native	-33.1 \pm 1.7	5	3
Carlson #3	CSV9-7	41.176	-91.000	North	Native	-39.0 \pm 0.2	5.5	4
Carole Leigh	CSV17-15	30.790	-87.780	South	Seedling	Flat	6	4
Carter	CSV5-1	30.411	-88.828	South	Seedling	-33.7 \pm 0.1	5	3
Cherokee	CSHQ10.3-1	31.726	-98.973	South	Cross	Flat	6	5
Chetopa	CSV9-4	37.023	-95.046	North	Native	-33.1 \pm 1.2	2	2
Chickasaw	CSHQ11.3-1	31.726	-98.973	South	Cross	Flat	8	7
Chief	CSV9-2	37.806	-88.262	North	Native	-34.8 \pm 0.5	5	4
Choctaw	CSHQ2.3-1	31.726	-98.973	South	Cross	-33.2 \pm 0.3	5	4
Clark	CSV11-10	31.105	-98.505	South	Native	Flat	4	2.5
Colby	CSV9-3	38.679	-89.309	North	Native	-34.4 \pm 0.5	4	2
Comanche	CSHQ1.3-1	31.726	-98.973	South	Cross	-38.3 \pm 0.6	5	4
Dependable	CSV6-2	30.411	-88.828	South	Cross	-34.1 \pm 1.1	4.5	3
Desirable	CSV5-2	30.411	-88.828	South	Cross	-33.5 \pm 0.4	6	4
Dixie	CSV17-11	30.790	-87.780	South	Seedling	Flat	7	6
Elliott	CSV2-2	30.631	-87.056	South	Seedling	-26.3 \pm 0.2	6.5	6
Esnel	CSV17-21	31.000	-87.500	South	Seedling	-33.8 \pm 0.3	7	5
Evans	CSV11-12	29.867	-96.817	South	Seedling	-33.5 \pm 0.3	5	3.5
Evers	CSV11-13	33.188	-97.064	South	Seedling	Flat	7	6
EW 7-22	CSV16-22	29.451	-96.334	South	Hybrid	Flat	5	3
EW7-25	CSV16-23	29.451	-96.334	South	Hybrid	-33.2 \pm 0.0	6	4
Farley	CSV6-5	30.800	-85.020	South	Seedling	Flat	5	3
Fayette	CSV11-16	29.899	-96.872	South	Seedling	-34.0 \pm 0.5	4	4
Forkert	CSV5-5	30.411	-88.828	South	Cross	-31.9 \pm 0.2	5.5	3.5
Foster	CSV12-2	29.461	-97.658	South	Native	-28.4 \pm 0.4	6	5
Frutoso	CSV11-14	25.420	-102.172	South	Native	Flat		
Giles	CSV2-3	37.062	-95.060	North	Native	-36.1 \pm 1.8	3.5	2
Gormely	CSV12-6	35.433	-96.305	North	Native	-35.4 \pm 0.3	2.5	2
Govett	CSV12-7	29.568	-97.885	South	Native	-34.4 \pm 0.4	5.5	4.5
Greenriver	CSV19-12	37.899	-87.482	North	Native	-37.9 \pm 1.4	5.5	4.5
Hirschi	CSV19-14	38.064	-94.238	North	Native	-34.7 \pm 0.9	5	4
Hodge	CSV19-7	39.174	-87.635	North	Native	-36.7 \pm 0.3		
Hollis	CSV12-13	31.100	-98.514	South	Native	Flat	5	4
Hughes	CSV6-1	30.411	-88.828	South	Seedling	-33.9 \pm 1.1	5.5	4
Humble	CSV12-17	29.087	-99.875	South	Native	-34.3 \pm 0.4	7	6
Ideal	CSV12-18	32.763	-98.718	South	Native	Flat	4	2
Jackson	CSV8-7	30.411	-88.828	South	Seedling	-35.4 \pm 2.2	3	2
James (LA)	CSV5-7	32.335	-91.023	South	Seedling	-35.1 \pm 0.3	5.5	5
Johnson(KS)	CSV12-20	37.176	-98.820	North	Native	-32.6 \pm 0.0	3	2
Jubilee	CSV8-15	30.417	-87.667	South	Seedling	Flat	5	4
Kanza	CSHQ13-9	31.726	-98.973	South	Cross	-33.8 \pm 0.2	5	5
Kiowa	CSHQ13-3	31.726	-98.973	South	Cross	-28.7 \pm 0.5	6	4
Koko	CSV17-23	30.125	-91.833	South	Seedling	Flat	6	4
Late	CSV13-3	31.374	-98.677	South	Native	-37.0 \pm 0.9	2	1
Longfellow	CSV13-4	31.193	-98.847	South	Native	-26.2 \pm 0.3	6	5
Mahan	CSV6-6	33.058	-89.588	South	Seedling	-27.6 \pm 0.0	7	6
Mahan-Stuart	CSV8-4	30.545	-83.870	South	Seedling	Flat	6	4
McCulley	CSV21-4	31.723	-98.958	South	Native	-34.8 \pm 0.9	6	4
McMillan	CSV17-7	30.790	-87.780	South	Seedling	-34.6 \pm 0.3	4	4
Melrose	CSV17-22	31.961	-93.348	South	Seedling	Flat	6	5
Mississippi 10	CSV7-3	32.730	-89.700	South	Seedling	Flat	2	2
MO-AES-2	CSV19-13	38.959	-92.343	North	Native	-39.2 \pm 0.6	3	2
Mobile	CSV17-20	30.417	-88.225	South	Seedling	Flat	6	4
Mohawk	CSHQ6.3-1	31.726	-98.973	South	Cross	Flat	5	4
Moneymaker	CSV7-5	32.339	-91.024	South	Seedling	-31.5 \pm 0.2	7	6
Montgomery	CSV16-24	32.516	-93.732	South	Seedling	-33.9 \pm 0.4	3	2
Moore	CSV2-4	30.411	-83.953	South	Seedling	Flat	6	5.5
MX5-1.7	CSP16-9	23.405	-99.381	South	Native	Flat		
N1-62	CSV11-19	32.300	-106.700	South	Cross	-38.0 \pm 0.5	5.5	4
N2-43	CSV12-1	32.300	-106.700	South	Cross	Flat	5	5

(Continued on next page)

Table 2. (Continued) Locality, temperature of the onset of the low temperature exotherm (LTE) (\pm SE), and budbreak data for 112 pecan cultivars.

Plant ID	Inventory designation	Latitude °N	Longitude °W	Region	Source	LTE (°C)	Budbreak	
						1999	2004	2005
Navaho	CSHQ13-8	31.726	-98.973	South	Cross	Flat	8	7
NC4	CSV19-15	43.200	-79.300	North	Seedling	-37.9 \pm 0.1	5	3
Nelson	CSV6-7	30.351	-89.398	South	Seedling	-37.0 \pm 0.5	7	6
Nugget	CSV13-7	31.837	-98.396	South	Native	-26.9 \pm 1.2	3.5	2.5
Number 54	CSV13-5	34.360	-106.100	South	Cross	-27.3 \pm 0.9	6.5	5
Oconee	CSHQ13-7	31.726	-98.973	South	Cross	-35.5 \pm 0.9	5	4
Oklahoma	CSV13-9	34.174	-97.143	North	Seedling	-26.9 \pm 0.2	4	2.5
Oliver	CSV4-1	30.852	-99.772	South	Native	-32.2 \pm 1.1	5	4
Osage	CSHQ13-5	28.594	-98.991	South	Cross	-34.4 \pm 0.1	5	4
Owens	CSV8-1	34.440	-90.495	South	Seedling	-36.3 \pm 0.1	7	6
Pointe Coupee	CSV8-2	30.734	-91.433	South	Native	-34.0 \pm 0.5	7	5
Prilop	CSV14-17	29.424	-96.940	South	Native	-38.7 \pm 0.4	3	3
Ripe Early	CSV13-13	35.520	-97.240	North	Native	-34.2 \pm 0.5	6.5	5
Risien #1	CSV13-14	31.249	-98.596	South	Native	Flat	6	5
Roth	CSV13-15	29.248	-97.329	South	Native	-34.8 \pm 0.4	6	4
San Felipe	CSV3-2	29.732	-100.896	South	Native	Flat	4.5	3.5
Schaeffer	CSV7-4	30.411	-88.828	South	Seedling	-35.6 \pm 0.3	6	4
Schley	CSV6-11	30.366	-88.556	South	Seedling	Flat	6	4
Schutz #1	CSV13-16	29.476	-97.550	South	Native	-28.2 \pm 0.5	2.5	2
Shawnee	CSHQ8.3-1	31.726	-98.973	South	Cross	Flat	6	5
Shoshoni	CSHQ13-1	31.726	-98.973	South	Cross	-30.1 \pm 1.9	7	6
Sioux	CSHQ5.3-1	31.726	-98.973	South	Cross	-32.7 \pm 0.1	6	5
Spence (MO)	CSV9-16	36.825	-93.130	North	Native	-34.3 \pm 0.6	2	1
Squirrels Delight	CSV13-19	31.249	-98.596	South	Native	-38.9 \pm 0.0	5	4
Stuart	CSV7-6	30.366	-88.556	South	Seedling	-31.0 \pm 1.4	4	2
Surprize	CSV7-11	30.406	-87.684	South	Seedling	-31.8 \pm 1.4	6	4
Syrup Mill	CSV17-9	30.694	-88.043	South	Seedling	Flat	7	6
Tejas	CSHQ13-2	31.726	-98.973	South	Cross	-34.3 \pm 0.2	6	4
Tinker	CSV17-19	31.180	-85.280	South	Seedling	-34.7 \pm 0.2	7	5
TSCN-88	CSV14-12	29.522	-97.491	South	Native	Flat	6	3
Van Deman	CSV3-3	30.087	-90.905	South	Seedling	-30.1 \pm 1.7	7	4
Wallops Island	CSV9-15	37.719	-75.666	South	Seedling	-39.7 \pm 0.0	3.5	3
Waukeenah	CSV3-5	30.411	-83.953	South	Seedling	-26.1 \pm 0.2	9	7
Weise	CSV20-4	39.386	-93.221	North	Native	-34.8 \pm 0.7	2	2
Wichita	CSHQ3.3-1	31.726	-98.973	South	Cross	-31.0 \pm 1.7	6	6
Williamson	CSV14-7	34.404	-96.826	North	Native	-39.4 \pm 0.1	3	2
Wilson	CSV15-12	38.000	-94.392	North	Hybrid	-36.4 \pm 0.4	3	2
Woodroof	CSV17-10	33.270	-84.290	South	Seedling	Flat	7.5	6.5
Woodside Early	CSV7-1	31.311	-92.445	South	Seedling	-26.5 \pm 0.3	5	3

Table 3. Average temperature of the onset of the low temperature exotherm (LTE) and budbreak classification for cultivars originating in the northern and southern regions.^a

Region	Cultivars #	Flat fraction	LTE (°C)	Budbreak	
				2004	2005
South	93	0.39	-32.9 \pm 0.4 a	5.4 \pm 0.2 a	4.2 \pm 0.2 a
North	19	0.11	-35.4 \pm 0.7 b	3.9 \pm 0.4 b	2.7 \pm 0.3 b

^aMeans and SEs are provided. Significant differences were identified using *t* tests.Letters represent significant differences between means as identified by a Tukey means separation test ($\alpha < 0.05$).

Some pecan DTA traces revealed multiple intermediate exotherms (Fig. 2). These exotherms may result from freezing events that occur in different tissue types within the dormant budwood (Ketchie and Kammereck, 1987), although these exotherms do not necessarily correlate with freezing injury (Quamme et al., 1972a). The presence of additional exotherms may be dependent on the phase of acclimation and the time of sampling (Ketchie and Kammereck, 1987; Quamme et al., 1972a). Multiple exotherms have been reported during deacclimation and may also represent the ability of tissue types to supercool. The multiple exotherms exhibited in pecan dormant budwood could indicate a lack of full acclimation attained by trees at the Texas sampling location. In contrast, a correlation was identified between pecan cultivars and the temperature of the

LTE in dormant budwood originating from Kansas and sampled in January (Rajashekar and Reid, 1989). The effectiveness of LTEs in predicting freezing injury appears to be dependent on sampling location.

Cultivar comparison. When all the cultivars collected from the College Station, TX, worksite with LTE were compared across the four storage time intervals, no significant changes in LTE occurred during storage until after 120 d of storage when the average LTE (if present) was significantly warmer (data not shown). In subsequent analyses, all data collected after 120 d of storage were not included in analyses. Pecan cultivars, seedlings, or breeding program crosses were classified according to their location of origin (Fig. 1). Inventories from the northern region had later budbreak times in both 2004 and 2005 than cultivars from the southern region

(Tables 2 and 3). Although all budwood was sampled from the College Station, TX, worksite, 39% of the cultivars originally from the southern regions had unresolved or "flat" LTE compared with 11% of the cultivars originally from the northern regions with flat LTE (Table 3). The flat LTE observed in the southern pecan materials may result from a reduced capacity for cold acclimation in materials that are not native to regions that experience severe cold temperatures. We believe that these flat LTE are distinctly different from the lack of LTE observed in extremely cold-hardy materials from northern regions (George et al., 1974). The lack of LTEs in some samples in the present study suggest that budwood did not become fully hardened in the Brownwood orchard at the January sampling date.

t tests revealed significant differences among the LTEs of -32.9 °C from the southern region and the LTE of -35.4 °C from the northern region, although all dormant budwood was collected from trees grown in College Station, TX. The northern region also had later budbreak in both 2004 and 2005. Thus, DTA can be used to separate the more cold-hardy northern materials from the less hardy southern materials when accessions are grown in a common orchard (Table 3).

Stem and apical floral bud LTEs could be correlated with killing temperatures in pecan (Rajashekar and Reid, 1989). Our xylem DTA data complement data previously published that suggest that LTEs occur at higher temperatures as pecan buds dehard in the spring (Rajashekar and Reid, 1989). However, LTEs were not observed for all accessions. Accessions native to the south were more likely to have flat traces that did not reveal useful exotherm data. These samples were likely not amenable to thermal analysis as a result of a lack of supercooled water detected by our DTA procedure.

Pecan cultivars were classified into improvement status categories of native, seedling, crosses, or hybrids (between different origin localities). It was hypothesized that named native cultivars that are clones of wild accessions native to the United States could have LTE more strongly correlated with origin locality than either seedlings or named cultivars from breeding programs. In our analyses, the temperature of LTE was not significantly affected by the improvement status of the pecan cultivars (data not shown).

Performance of two cultivars, Prilop and Nelson, is especially noteworthy. 'Nelson' is a Mississippi seedling selection made by William Nelson in 1904 (Nelson, 1904). Its tendency to break buds early in Brownwood was noted by Louis Romberg, the first pecan breeder in the USDA Agricultural Research Service (Romberg, 1966). 'Nelson' was rated at bud stages 7 and 6 in data reported here (Table 2). The early bud growth makes 'Nelson' very susceptible to late winter or early spring freezes, like the one experienced at Brownwood, TX, on 8 Apr. 2003. The tree was rated at bud stage 4 on 1 Apr. 2003 and was among the most severely damaged when temperatures dropped to -2°C for several hours. Shoots were killed back past the eighth bud of the previous season's growth but forced new growth with aberrant blooms. 'Prilop' is a native selection from the Lavaca River, originally growing 4 km south of Hallettsville in Lavaca County, TX (Grauke and Thompson, 1997). The tree is unusually late in breaking buds in the spring as indicated by its rating of 3 in both years reported here (Table 2), making it comparable in phenology to many northern cultivars. 'Prilop' was not present in the Brownwood collection during the 2003 freeze. 'Nelson' and 'Prilop' had LTEs of -37°C and -38°C , respectively (Table 2), placing them in a category with the most hardy northern cultivars. Obviously, information provided by LTEs must be qualified by an understanding of cultivar phenology. At this time, the cost of LTE information is not justified by the quality of information it provides.

LTE data generally support recorded information about the relationship between hardiness and origin locality. Pecans that originated or were developed for more northerly localities are more likely to have discernible and lower LTE than those adapted to warmer southern climates. Because all the accessions used in comparisons were collected from common orchards, it is interesting that differences in LTE were observed. This suggests that the presence and extent of LTE have genetic components because all cultivars experienced similar winter acclimation conditions.

Both budbreak and LTE data are correlated to the region of origin and cultivars retain these properties when grown in a common environment. It follows that either phenotypic trait could be used as a possible predictor of origin and thus potential hardiness of uncharacterized cultivars. As a result of the relative ease of collecting budbreak data and the more challenging acquisition of DTA data, which is dependent on winter conditions, rootstock, and moisture content, it is suggested that budbreak data serve as a preliminary source of origin and potential hardiness of pecan cultivars.

Literature Cited

- Daws, M.I. and H.W. Pritchard. 2008. The development and limits of freezing tolerance in *Acer pseudoplatanus* fruits across Europe is dependent on provenance. *Cryo Letters* 29:189–198.
- George, M.F., M.J. Burke, H.M. Pellett, and A.G. Johnson. 1974. Low temperature exotherms and woody plant distribution. *HortScience* 9:519–522.
- Graham, P.R. and R. Mullin. 1976. The determination of lethal freezing temperatures in buds and stems of deciduous azalea by a freezing curve method. *J. Amer. Soc. Hort. Sci.* 101:3–7.
- Grauke, L.J. 2008. Monitoring bud growth. 12 Sept. 2008. <<http://extension-horticulture.tamu.edu/carya/Manual/BUDBRK.html>>.
- Grauke, L.J. and J.W. Pratt. 1992. Pecan bud growth and freeze damage are influenced by rootstock. *J. Amer. Soc. Hort. Sci.* 117:404–406.
- Grauke, L.J. and T.E. Thompson. 1996. Variability in pecan flowering. *Fruit Var. J.* 50:140–150.
- Grauke, L.J. and T.E. Thompson. 1997. Pecan. In: Register of new fruit and nut varieties. Brooks and Olmo, List 38. *HortScience* 32:793–796.
- Grauke, L.J. and T.E. Thompson. 2008. Pecan, p. 421–425. In: Janick, J. and R.E. Paull (eds.). *Encyclopedia of fruit and nuts*. CAB International, Wallingford, UK.
- Ketchie, D.O. and R. Kammereck. 1987. Seasonal variation of cold resistance in *Malus* woody tissue as determined by differential thermal analysis and viability tests. *Can. J. Bot.* 65: 2640–2645.
- Montano, J.M., M. Rebhuhn, K. Hummer, and H.B. Lagerstedt. 1987. Differential thermal analysis for large-scale evaluation of pear cold hardiness. *HortScience* 22:1335–1336.
- Nelson, W. 1904. The Nelson pecan. *The Nut Grower* 2:134.
- Quamme, H., C. Stushnoff, and C.J. Weiser. 1972a. The relationship of exotherms to cold injury in apple stem tissues. *J. Amer. Soc. Hort. Sci.* 97:608–613.
- Quamme, H.A., C. Stushnoff, and C.J. Weiser. 1972b. Winter hardiness of several blueberry species and cultivars in Minnesota. *HortScience* 7:500–502.
- Quamme, H., C.J. Weiser, and C. Stushnoff. 1973. The mechanism of freezing injury in xylem of winter apple twigs. *Plant Physiol.* 51:273–277.
- Quamme, H.A. 1991. Application of thermal analysis to breeding fruit crops for increased cold hardiness. *HortScience* 26:513–517.
- Rajashekar, C.B. and W. Reid. 1989. Deep supercooling in stem and bud tissues of pecan. *HortScience* 24:348–350.
- Romberg, L.D. 1966. Notes on varieties used in breeding of which progeny were fruited in the years through 1966. US Pecan Field Station, Brownwood, TX. Unpublished records. USDA-ARS.
- Sanderlin, S. 2000. Pecan scion cultivar effects on freeze susceptibility of the rootstock. *J. Amer. Pomological Soc.* 54:188–193.
- Smith, M.W. 2000. Cultivar and mulch affect cold injury of young pecan trees. *J. Amer. Pomological Soc.* 54:29–33.
- Smith, M.W. 2002. Damage by early autumn freeze varies with pecan cultivar. *HortScience* 37:398–401.
- Smith, M.W., B.L. Carroll, and B.S. Cheary. 1992. Chilling requirement of pecan. *J. Amer. Soc. Hort. Sci.* 117:745–748.
- Smith, M.W., B.S. Cheary, and B.L. Carroll. 2001. Rootstock and scion affect cold injury of young pecan trees. *J. Amer. Pomological Soc.* 55: 124–128.
- Sparks, D. 1991. Geographical origin of pecan cultivars influences time required for fruit development and nut size. *J. Amer. Soc. Hort. Sci.* 116:627–631.
- Sparks, D. 1993. Chilling and heating model for pecan budbreak. *J. Amer. Soc. Hort. Sci.* 118: 29–35.
- Sparks, D. 2005. Adaptability of pecan as a species. *HortScience* 40:1175–1189.
- Sparks, D. and J.A. Payne. 1977. Freeze injury susceptibility of non-juvenile trunks in pecan. *HortScience* 12:497–498.
- Thompson, T. and R.E. Hunter. 1985. 'Pawnee' pecan. *HortScience* 20:776.
- Thompson, T.E., L.J. Grauke, W. Reid, M.W. Smith, and S.R. Winter. 1997. 'Kanza' pecan. *HortScience* 32:139–140.
- Thompson, T.E., W. Reid, and L.J. Grauke. 2008. 'Lakota' pecan. *HortScience* 43:250–251.
- Thompson, T.E., E.F. Young, Jr., and H.D. Petersen. 1991. 'Osage' pecan. *HortScience* 26:1098–1099.
- Vogel, K.P., M.R. Schmer, and R.B. Mitchell. 2005. Plant adaptation regions: Ecological and climatic classification of plant materials. *Rangeland Ecol. Manag.* 58:315–319.
- Wood, B.W., L.J. Grauke, and J.A. Payne. 1998. Provenance variation in pecan. *J. Amer. Soc. Hort. Sci.* 123:1023–1028.